Overtopping of Walls and Stilling Basin Failure

Best Practices in Dam and Levee Safety Risk Analysis

Part F – Hydraulic Structures

Chapter F-2

June 2017

US Army Corps of Engineers®

Objectives

- Understand the factors and mechanisms that affect spillway chute wall overtopping failure
- Understand how to construct an event tree to represent spillway chute wall overtopping failure
- Understand how to consider stilling basin sweepout and failure

Dam and Levee Overtopping of Walls and Stilling Basin Failure Modes

- Failure of dams and levees due to overtopping is a common failure mode
  - 30% of dam failures in U.S. are attributed to overtopping
  - Many spillways are under designed for large discharges and could be vulnerable to chute capacity issues.
- Many older dams and levees may have been designed for floods that no longer represent a remote flood event and design flood estimates have increased

Case History: Failure of El Guapo Dam, Venezuela

- El Guapo Dam spillway failed December 16, 1999 as a result of spillway failure from chute wall overtopping
  - Hydrology to size spillway based on hydrologic data transferred from another drainage basin (site specific hydrology is best)
  - During spillway construction chute walls were overtopped during a flood which triggered a new flood study (added a tunnel spillway)
- El Guapo Dam never overtopped
- Overtopping of chute walls initiated erosion of backfill behind chute walls and undermining and failure of spillway chute
- Headcutting progressed upstream and led to reservoir breach
- Spillway foundation consisted of decomposed rock, which was erodible

Approach Channel to Spillway

Spillway Chute

Sweepout of spillway stilling basin

Overtopping Along Entire Length of Chute

Overtopping of Upstream Chute Walls

Breach Formation Nearing Completion

Headcutting Progressed to Reservoir

Aftermath of Reservoir Breach

Spillway Wall Overtopping and Stilling Basin Failure Key Concepts and Factors

- Spillway Design Discharge
- Spillway Discharges (Depth and Duration)
- Convergence and Divergence of Chute Walls
- Superelevation of Chute
- Air Bulking in Flow
- Cross Waves in Spillway Chutes
- Spillway Configuration
- Ball Milling
- Stilling Basin Sweepout

Spillway Design Discharge

- The discharge that the spillway was designed for will determine the flow capacity of the chute and stilling basin
- If flood routings indicate spillway design discharge will be exceeded for some flood events, chute overtopping becomes more likely
- Whether overtopping occurs will be influenced by freeboard provided in the original design and other factors (cross waves and air bulking)
- Stilling basin walls not typically a concern regarding overtopping (distance from crest and tailwater)

Spillway Discharges

- Routings of specific frequency floods provides discharges and discharge durations
- Water surface profiles are calculated for discharges obtained from frequency flood routings to provide flow depths and velocities
- Cross waves and air bulking not estimated

Convergence and Divergence of Chute Walls

- Best performance of spillway chute is obtained when confining sidewalls are parallel to the flow direction and flow distribution is uniform
- In order to optimize the spillway design, chute may be narrower or wider than the crest structure or terminal structure
- If convergence is too abrupt, uneven flow distribution and cross waves can develop

Convergence and Divergence of Chute Walls

- Angular variation of flow boundaries should be limited to:

$$\tan\alpha = \frac{1}{3F}$$

- Froude number:

$$F = v/\sqrt{gd}$$

- α = angular variation of sidewall w/respect to channel centerline

Superelevation of Chute

- Curved spillway chutes result in a rise in water surface on the outside of the chute and a depression of the surface along the inside wall due to centrifugal force
- Rise in water surface for supercritical flow in chutes is about twice that of subcritical flow
- Standing waves can be generated with supercritical flow and simple curves in chute
- For curved chutes with supercritical flow, use of spiral transitions with circular curves and invert banking will reduce the wave heights

Superelevation of Chute

- The following equation provides increase in water surface along outside of curve due to superelevation:

$$\Delta y = CV^2W/gr$$

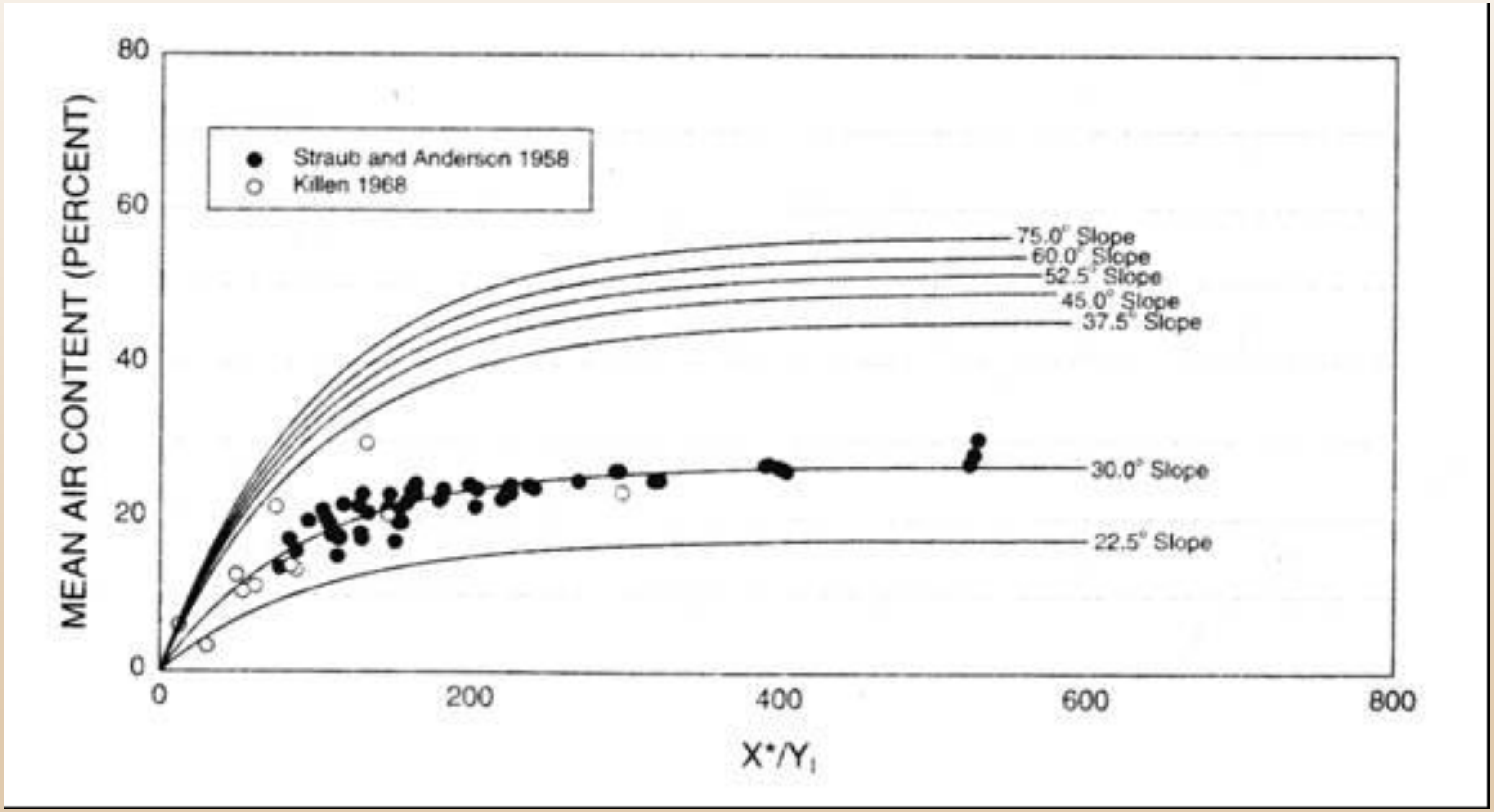
Air Bulking in Flow

- Air bulking will generally increase the depth of flow in chute and is not accounted for in many water surface profile models (ex. ZPROFILE)
- Air bulking occurs where turbulent water boundary layer reaches the water surface and air is introduced into the flow
- $d_b/d = 1/1\text{-}C$
  - d = flow depth (without aeration)
  - d_b = bulked flow depth to the top of the waves
  - C = mean air content
- Note – air bulking of flow in the turbulent layer will reach the surface and does not provide the benefit of preventing cavitation damage

Air Bulking: Mean Concentration of Entrained Air

C value from previous slide

(in percent by volume (from Wilhelms and Gulliver, 2005))



X* = distance from the point of inception to the location of interest
Y_i = depth of flow at the point of inception

Air Entrainment Point of Inception

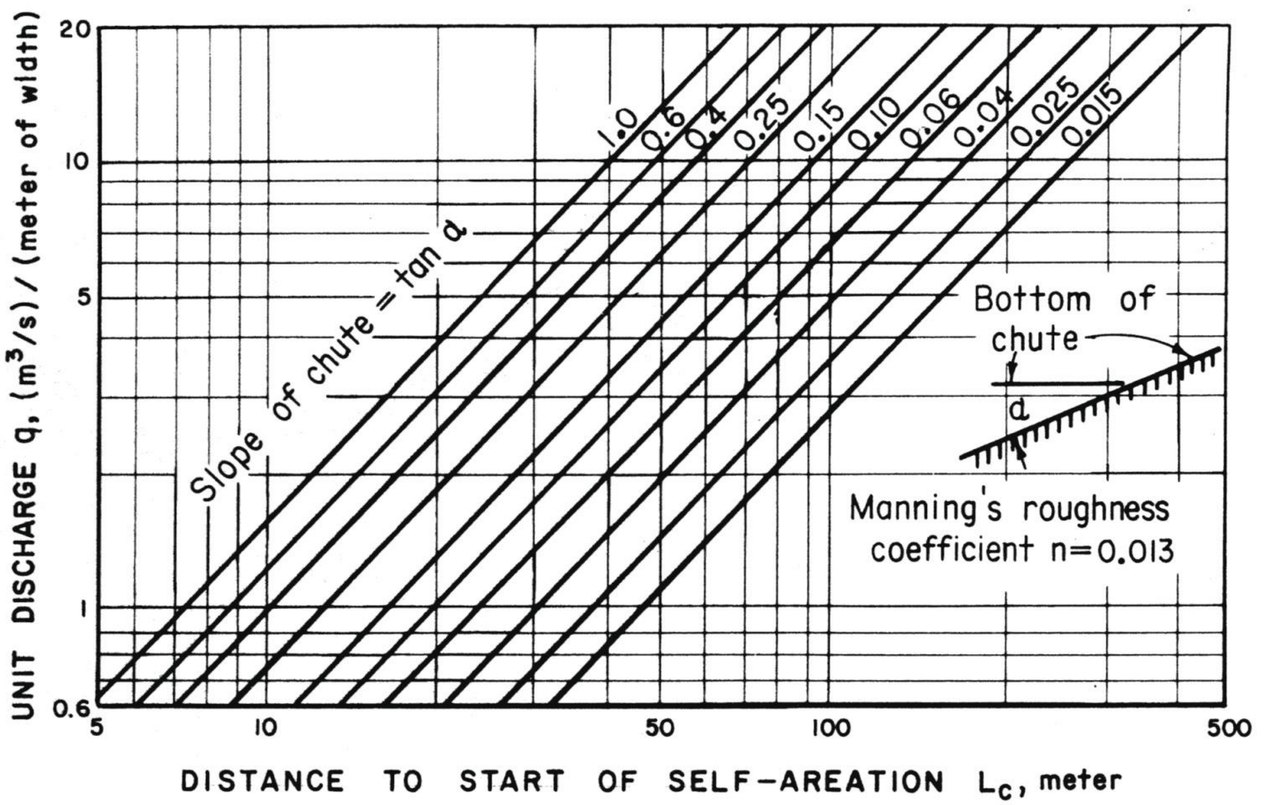


FIGURE 8.—*Location of inception of air entrainment.*

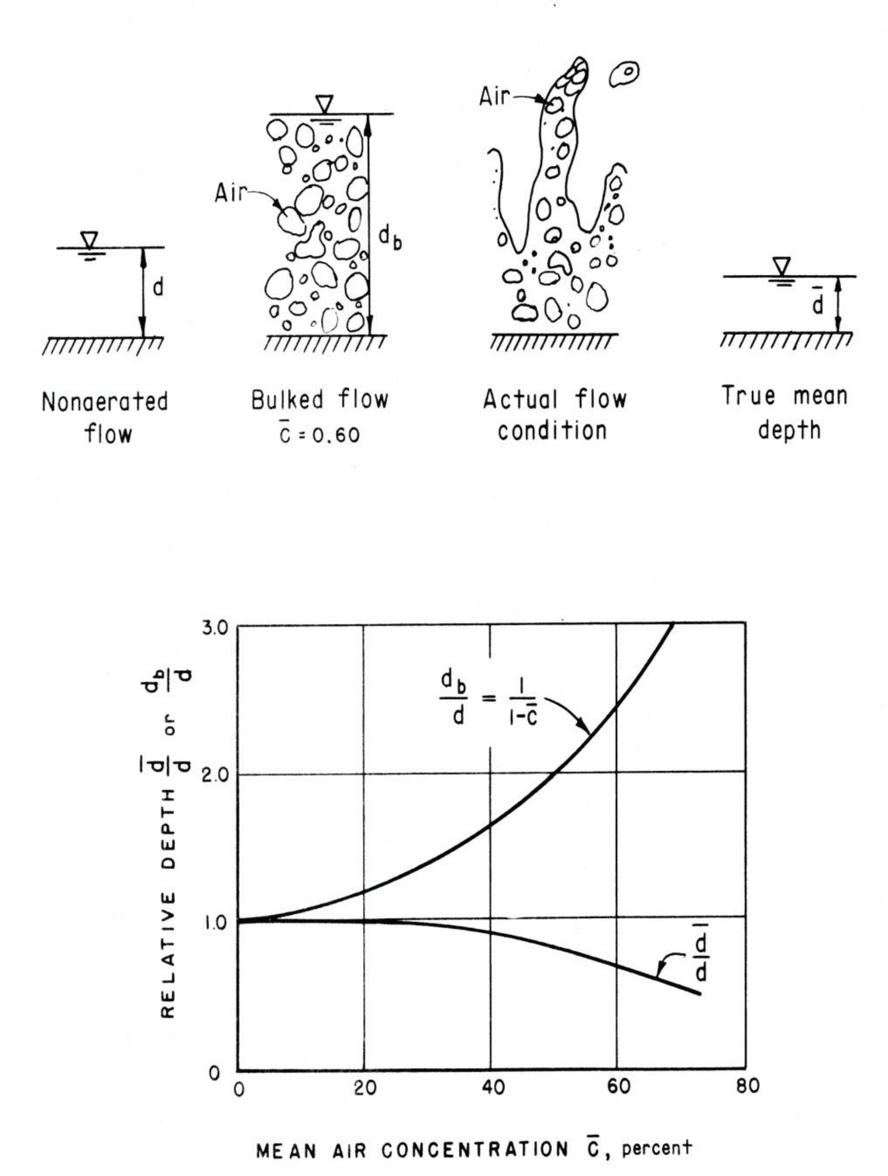
from Falvey (1980)

Folsom Dam Spillway – Air Entrainment

Air entrainment likely combination of:

- Turbulent flow under the spillway gate
- Flow down the steep chute (from turbulent boundary layer reaching surface)

Aerated Flow Depth Definitions



from Falvey (1980)

Air Bulking in Flow

- Bulked depth due to entrained air and entrapped air:
- $db/d = 1/1\text{-}(C_e + C_E)$; $C_E = 0.23$
- It has been found that the depth of flow decreases and the velocity increases compared to that calculated from the above equation as air concentration increases above 25 percent due to reduction in coefficient of friction for highly aerated flow (refer to Folsom spillway photograh)
- Note – air bulking of flow in the turbulent layer will reach the surface and does not provide the benefit of preventing cavitation damage

Erodibility of Foundation Materials

- Overtopping flows have the ability to erode backfill, then erode foundation materials, which can lead to undermining of the chute
- Soil foundations are generally more erodible than rock foundations
- Foundation can scour and headcutting can initiate
- Design notes:
  - Foundations for spillway chutes should be evaluated during design phase and founded on rock (where possible)
  - If spillway chute is founded on soils (not economic to over excavate to rock foundation), measures to prevent erosion should be included

Spillway Configuration and Intervention

- Uncontrolled spillways are not regulated and provide little or no opportunity to reduce discharges or redirect flows should problems develop during a flood
- Gate spillways may allow for reduction in spillway flows and reliance on reservoir storage space, especially for smaller floods, or brief closure for emergency repairs
- For spillways with multiple gates it may be possible to operate gates to direct flow away from damaged area, at least in upper chute

Wall Overtopping Event Tree

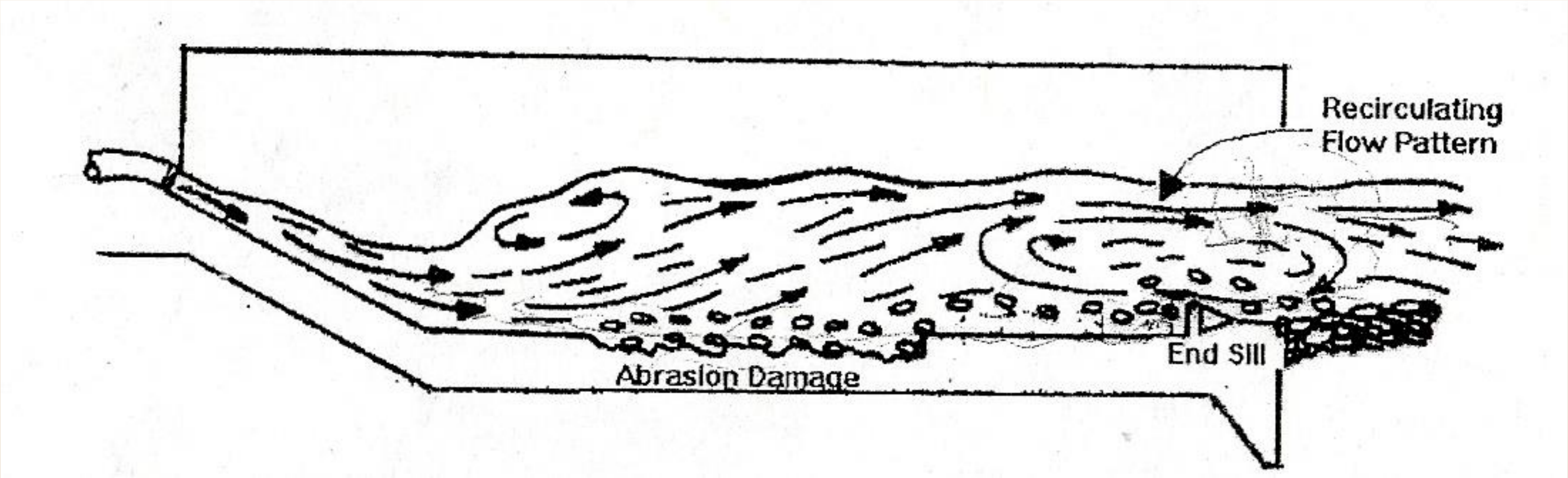
1. Starting Res Elevation
2. Flood Load Range
3. Spillway Flows Overtop Chute Walls
4. Erosion Initiates in Spillway Backfill
5. Chute Undermined
6. Headcut Initiates
7. Unsuccessful Intervention
8. Breach Forms

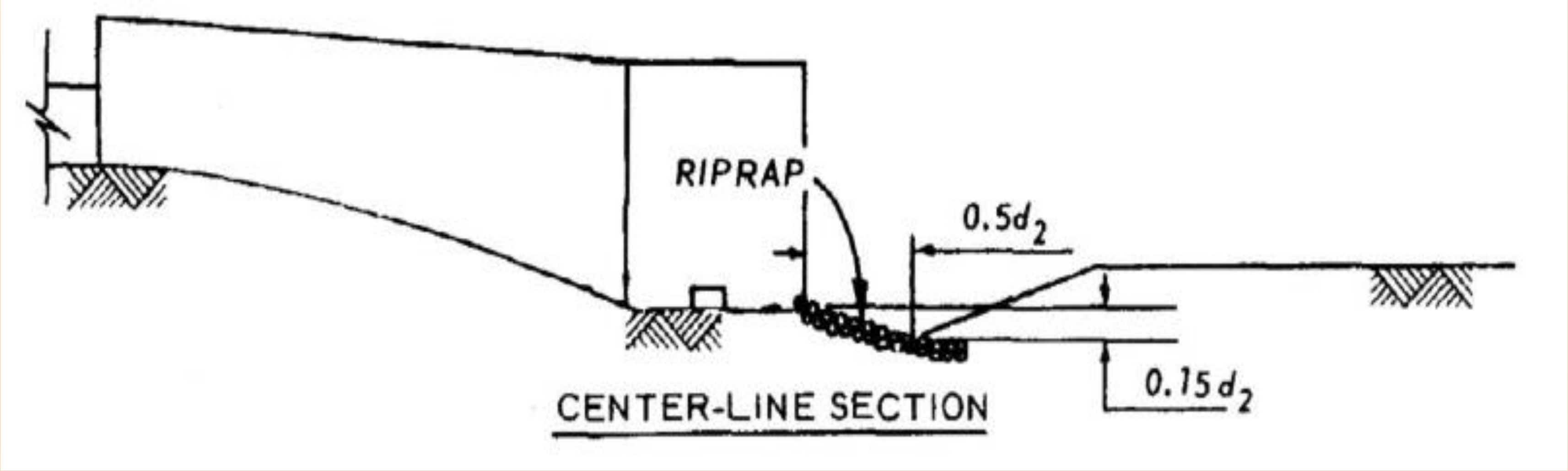
Wall Overtopping Event Tree

Ball Milling – Stilling Basin

- Ball milling can expose the spillway foundation and lead to scour and headcutting
- Ball milling is a mechanism where material trapped in a hydraulic jump stilling basin is circulated within the flow and abrades and erodes the stilling basin
- Given enough time, the entire basin floor can be removed, exposing the stilling basin foundation
- Possible to compromise reinforcing steel and destabilize wall

Ball Milling – Stilling Basin and Downstream Scour





Echo Dam Spillway

Ball Milling – Stilling Basin Case Histories

Dam	Agency	Concrete Compressive Strength, lb/in^2	Depth of Erosion, in	Duration of Spillway Flows, Days	Abrasion/Erosion Rate in/day
Libby	USACE	5000	24	720	1 inch / 30 days
Dworshak	USACE	n/a	3	53	1 inch / 18 days
Bull Shoals	USACE	3600 (28 day)	18	224	1 inch / 12 days
Pomona	USACE	5000 - 5600	2	960	1 inch / 480 days
Chief Joseph	USACE	n/a	12	420	1 inch / 35 days
Table Rock	USACE	n/a	3	45	1 inch / 15 days
Oologah	USACE	4000 - 5000	17	1100	1 inch / 65 days
Folsom	Reclamation	n/a	30	122	1 inch / 4 days

Stilling Basin Sweepout

- Occurs in hydraulic jump stilling basins
- Tailwater is insufficient to allow the jump to develop or be maintained
- Sweepout can lead to erosion in downstream channel or floatation of stilling basin followed by scour, headcutting and breach
- Evaluate by comparing conjugate depths for various flows to predicted tailwater elevation
- Note that failure progression of sweepout and ball milling have a similar progression event tree as the wall overtopping (losing foundation, headcutting, etc.)
  - Lose more material since failure occurs further downstream
  - Typically lower probability of failure than wall overtopping

Hydraulic Jump Stilling Basin

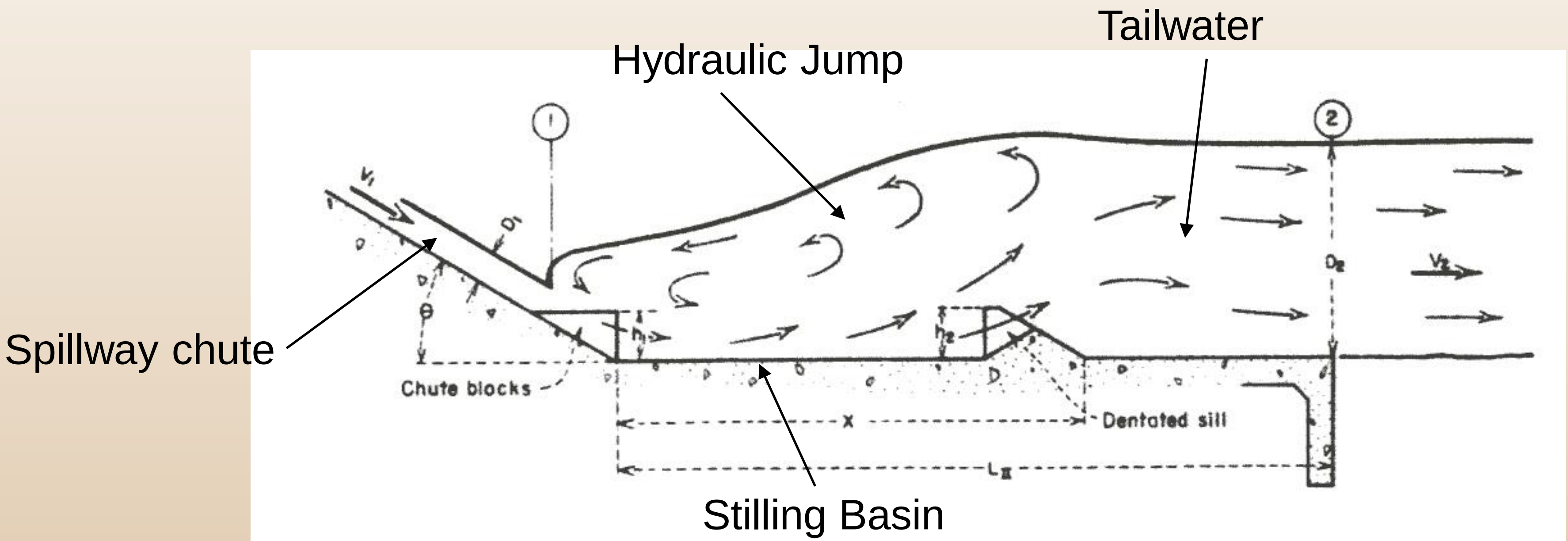


FIGURE 10.—*Definition of symbols (Basin II).*

Hydraulic Jump Stilling Basin

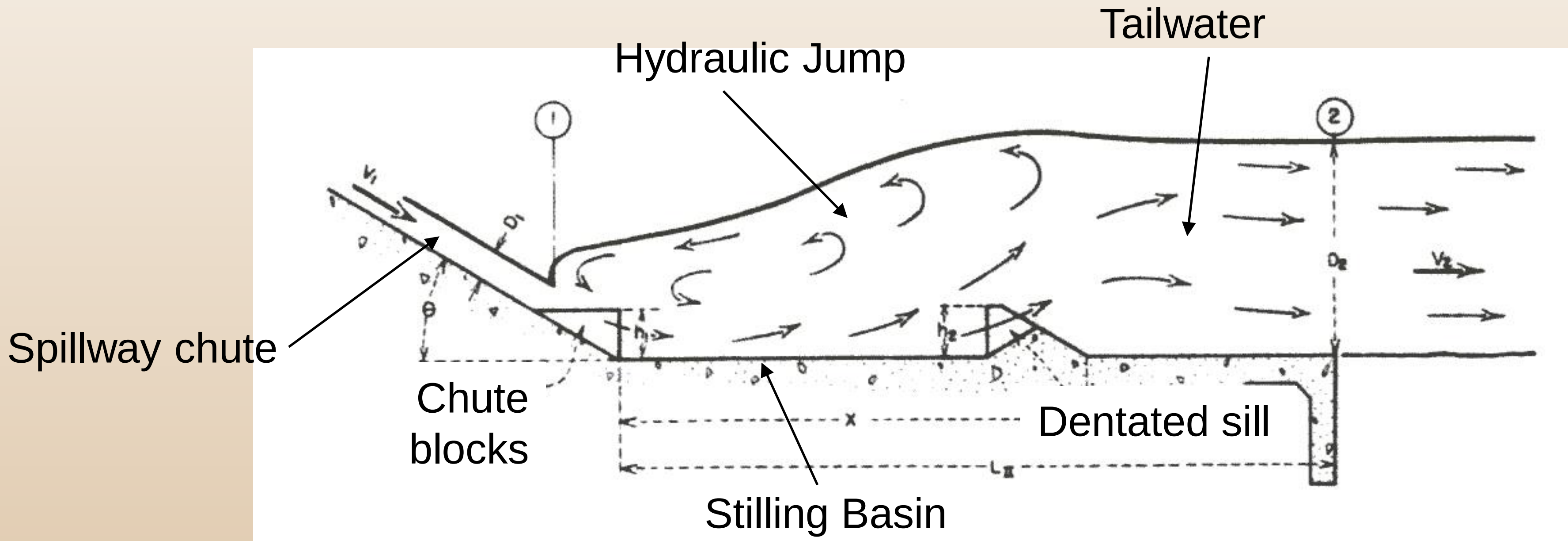


FIGURE 10.—*Definition of symbols (Basin II).*

- Sweepout - hydraulic jump occurs near end sill or in downstream channel
- Inflow design flood used to size stilling basin may not be largest storm
- Loss of tailwater control feature in downstream area

Questions

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F-2 Overtopping Walls/Stilling Basin Failure Example

- Consider a spillway with a concrete lined chute. The rectangular chute is 20-feet wide. The chute walls are 10 feet high. Estimate the annual probability that the chute walls will be overtopped at Station 10+00, using the information provided in the following Table 1. It was determined by analysis that air bulking and cross waves will not develop in the spillway chute.

Note:
Q (discharge) = V (velocity) * A (Area of flow)
Q = cfs
V = ft/s
A = ft^2

Table 1: Spillway Discharge and Flow Velocities in Spillway Chute, Station 10+00		
Frequency Flood, yr	Spillway Discharge, ft^3/s*	Flow Velocity, ft/s
1000	2000	40
10,000	7300	55
100,000	17,800	88
1,000,000	25,300	91

Example Solution

- The spillway chute is 20-foot wide with 10-foot high walls. The depth of flow for the frequency flood discharges can be determined from Q = VA, where Q is the discharge, V is the average flow velocity and A is the area of flow. Given Q and V, the area of the flow can be determined and then the depth of flow determined by dividing the flow area by the 20-foot chute width. The flow depths can then be compared to the 10 foot wall heights. Table 2 shows the flow depth calculations. Table 3 provides the annual probability of chute wall overtopping estimates and Table 4 provides the factors considered in the estimates.

Table 2 – Determination of Flow Depths				
Frequency Flood, yr	Spillway Discharge, ft^3/s	Flow Velocity, ft/s	Flow Area, ft^2	Flow Depth, ft
1000	2000	40	50	2.5
10,000	7300	55	133	6.6
100,000	17,800	88	202	10.1
1,000,000	25,300	91	278	13.9

Table 3 – Annual Probability of Chute Wall Overtopping			
Flood Load Range	Load Range Probability	Conditional Failure Probability	Annual Probability of Damage
> 1,000,000 yr	1E-06	0.999	1.0 E-06
100k – 1000k yr	9E-06	0.5 to 0.99	6.7E-06
10k – 100k yr	9E-05	0.001 to 0.5	2.3E-05
1k – 10k yr	9E-04	0	0
< 1k yr	0.999	0	0
Total			**3E-05**

Table 4 - Factors for Chute Wall Overtopping	
More Likely Factors	**Less Likely Factors**
Walls are predicted to overtop for flows representing floods equal to and greater than the 100,000-year flood	Air bulking is not a factor.
	Cross-waves are not a factor.
	Large amounts of freeboard for 1000- and 10,000-year floods.